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SCIENCE

Electron Spin Resonance in Organic Chemistry

Determination of structure and conformation of paramagnetic substances is demonstrated.

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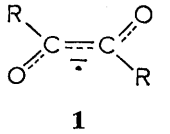
The contributions of electron spin resonance (ESR) spectroscopy to organic chemistry are diverse. Among the most obvious applications to free radicals in solution are those concerning the detection and identification of paramagnetic intermediates, the delocalization of an unpaired electron over a system of π and σ bonds, the equilibrium or dynamic geometry of free radicals, measurements of lifetimes of paramagnetic entities, and assignment of structure to the precursors of radical species. Before discussing each of these applications I shall review some of the aspects of the electron spin resonance experiment (*1*).

In a homogeneous magnetic field a free radical can have a number of energy states (referred to as spin states), depending on the relative orientation of the magnetic moments of the unpaired electron, the closely associated nuclear spins, and the applied magnetic field (contributions to the magnetic moment from orbital motion of the unpaired electron are not important for most organic free radicals). There are two orientations possible for the unpaired electron spin ($M_S = \pm \frac{1}{2}$), and there ($2M_I + 1$) orientations for each nuclear spin, where M_S and M_I are the electron and nuclear magnetic quantum numbers. For ^{1}H, ^{19}F, ^{13}C, and ^{15}N the value of M_I is $\frac{1}{2}$, while for ^{2}H and ^{14}N, M_I is 1. The total number of spin states is thus $2\pi\ (2\Sigma M_I + 1)$ and in a first-order spectrum a total of $\pi\ (2\Sigma M_I + 1)$ transitions, where $\Delta M_I = 0$, is observed. Figure 1 shows possible energy states, ($\Delta M_I = 0$) transitions, and the expected ESR spectrum for a system of an electron closely associated with one nitrogen nucleus and one hydrogen nucleus [$\pi\ (2M_I + 1) = 6$]. Not all spin states having the same value of ΣM_I for a given atom have exactly the same energy, and a higher degree of hyperfine splitting (second-order spectra) can sometimes be observed under conditions of excellent resolution (*2*).

Because of instrumental considerations associated with the signal-to-noise ratio, ESR spectra are nearly always recorded as first- (Fig. 1D) or second-derivative spectra. The absorption (Fig. 1C) or first-derivative spectra is defined by a set of hyperfine splitting constants, a *g*-factor, and a shape function. All three of these experimental quantities can be utilized in the study of organic radicals.

The hyperfine splitting constant (see Fig. 1B) is a constant that reflects the magnetic field of a given nucleus (H_{hf}) experienced by the electron. There is a difference in energy of the transition, where $\Delta M_S = 1$, in the presence and absence of the hyperfine magnetic field. For an unbound electron the energy of this transition is $\Delta E = h\nu = g\beta H$ or $\nu = 2.8 \times 10^6\ H$ where ν is the frequency in hertz, H the magnetic field in gauss, and β is the Bohr magneton. Most ESR measurements in solution are made with $\nu \cong 1 \times 10^{10}$ hertz, $H \cong 3500$ gauss, $\Delta E \cong 6.5 \times 10^{-17}$ erg/molecule $\cong$ 1 cal/mole. The difference in energy of this transition in the presence and absence of a hyperfine field will be very nearly $2.8 \times 10^6\ (H_{\mathrm{hf}})h$. The hyperfine splitting measures the probability that spin density at the nucleus of the atom is responsible for the hyperfine splitting, that is $|\ \psi\ |^2$, evaluated when the distance between the electron and nucleus is zero. There will be a finite value to $|\ \psi(\mathrm{O})\ |^2$ only when the electron is in an *s* orbital, or a hybridized orbital containing *s*-character. In the case of a hydrogen atom with a complete electron in the 1*s* orbital, the hyperfine splitting constant (a^{H}) is ~500 gauss (*3*). Any observed value of a^{H} can now be converted to a spin density at the hydrogen atom in question (ρ^{H}) by the relation, $\rho^{\mathrm{H}} = a^{\mathrm{H}}/500$. For other atoms correlations between spin density and hyperfine splitting constants are more complex (*4*).

The *g*-factor, defined by the center of the ESR spectrum (Fig. 1) and the equation $h\nu = g\beta H$, is a dimensionless constant that is 2.002319 for the ununbound electron. The value of the *g*-factor will reflect the structure and charge of a free radical, particularly when hetero atoms are involved, since orbital angular momentum of the electron can have an effect on the value of transition $\Delta M_S = 1$. For example, it has been found that for semidiones the *trans* structure (**1**) has a higher *g*-factor (as much as 0.01 percent) than the *cis* structure (**2**) (*5*).



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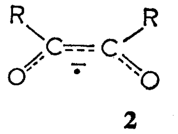

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The final criterion of the ESR spectrum is associated with the shape of the individual peaks. The absorption spectra of radicals in solution (Fig. 1C)

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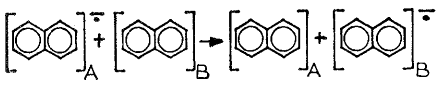
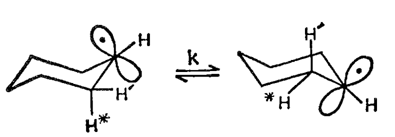
often approximate a Lorentzian-shaped curve. In this case the line width indicated in Fig. 1D ($\delta H'$) can be converted to the breadth at half height (ΔH) by the relation, $\Delta H = (3)^{1/2}(\delta H')$. The narrowest ESR lines observed are in the range of $\delta H' = 0.013$ gauss (*6*). Lines can be broadened for a number of reasons, and an analysis of such broadening can lead to valuable information about kinetic constants. The uncertainty principle limits the line width obtainable in the period of measurement (Δt) to $\Delta E \Delta t = g\beta\Delta H\Delta t \leq h/2$. The period for measurement may be limited by the chemical or magnetic lifetime of the species. Since an appreciable period of time is necessary to establish a Boltzmann population of energy states (Fig. 1) before the ESR absorption can be observed, and since free radicals are always generated in a saturated condition (that is, with equal population of the spin states ($M_S = \pm 1/2$), a radical that can be observed by ESR spectroscopy is not likely to show line broadening because of some irreversible process that leads to destruction of the species. On the other hand, electron transfer between identical molecules, such as naphthalene (*7*), will almost surely destroy the original magnetic-spin state with its discrete value of M_I^H (**1**). Similarly, a conformational



(1)

interconversion such as **3** ⇄ **4**, (*8*), which causes hydrogen atoms H′ and H* to exchange positions will destroy one spin state and create another if ΣM_I for a given type (axial or equatorial) of hydrogen atom changes.



(2)

3 **4**

H′ equatorial H′ axial
H* axial H* equatorial

The mean lifetime (τ) of a magnetic species is given by the equation, $\tau = h/(3)^{1/2}g\beta\pi\delta H'$, if the destruction of the magnetic spin state occurs by some random process such as in Eq. 1. In cases where a dynamic equilibrium, such as Eq. 2, causes a reversible shift in spin energy, the line broadening is somewhat more complicated, and more interesting results occur. Here the line broadening will be a function of the difference in the hyperfine splitting constant of a given nucleus in the two magnetic environments ($\Delta\nu$), and line coalescence may be observed when $\tau = 1/k = (1/(2)^{1/2}\pi\Delta\nu)$. This phenomenom will be illustrated later.

Detection and Identification of Paramagnetic Intermediates

Electron spin resonance has been used to verify the presence of free radicals where other evidence suggested their presence. Thus, the experimentally challenging observations of methyl, ethyl, propyl, and similar radicals as a result of radiation of the parent hydrocarbons with 2.8 Mev electrons is consistent with expectation (*8*). Similarly, the detection and identification of radical intermediates in vinyl polymerizations initiated by hydrogen peroxide and titanous ion is consistent with established theories (*9*).

$$H_2O_2 + Ti^{2+} \longrightarrow HO\cdot + Ti^{3+}$$
$$HO\cdot + CH_2{=}C(CH_3)CO_2H \longrightarrow HOCH_2\dot{C}(CH_3)CO_2H$$
$$\xrightarrow{CH_2{=}C(CH_3)CO_2H} HOCH_2C(CH_3)(CO_2H)CH_2\dot{C}(CH_3)CO_2H$$

The detection of a whole class of nitroxide radicals ($R_2NO\cdot$) prepared by oxidation of hydroxylamines by metal ions (*10*), by oxidation of amines with peroxides or peracids, (*11*), by alkali metal reduction of nitro compounds (*12*), or by photolysis of nitroso compounds (*13*), seems reasonable in view of previously established principles (see Chart 1) (*14*).

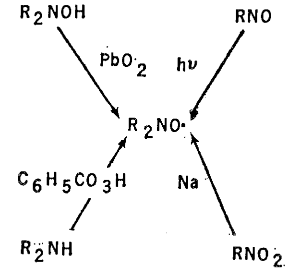
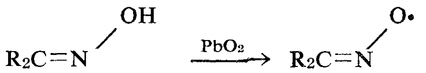


Chart 1

The extension of this work to iminoxy radicals ($R_2C{=}NO\cdot$), formed by oxidation of oximes, represents the discovery of a new class of free radicals that have an interesting electronic structure (*15*).



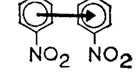
$$R_2C{=}N{-}OH \xrightarrow{PbO_2} R_2C{=}N{-}O\cdot$$

The detection of unexpected paramagnetic intermediates is naturally of interest to organic chemists. The identification of a single stable paramagnetic species in the oxidation of a variety of aliphatic ketones by traces of oxygen in basic solution is such an example (*16*). Since the same intermediate is formed by the oxidation of α-hydroxy ketones, by the reduction of α-diketones, and by the disproportionation of a mixture of diketone and α-hydroxy ketone in basic solution, the semidione structure seems secure (*17*).

$$RCOCH_2R' + (CH_3)_3CO^- \rightarrow \xrightarrow{CH_3SOCH_3} RC(O^-){=}CHR'$$
$$RC(O^-){=}CHR' + \text{trace } O_2 \longrightarrow RC(O\cdot){=}C(O^-)R'$$
$$RCOCH(OH)R' \overset{B^-}{\rightleftarrows} RC(O^+){=}C(O^-)R$$
$$RCOCOR' + RC(O^-){=}C(O^-)R' \rightleftarrows 2\,RC(O\cdot){=}C(O^-)R'$$

Another example of an unexpected formation of a paramagnetic product involves the disproportionation of *p*-nitrotoluene in basic solution (*18*). This process, discovered by use of ESR spectroscopy, is actually a fairly general process for substituted methanes in which the substituent is both acid-strengthening and easily reduced.

$$p\text{-}NO_2C_6H_4CH_2^- + P\text{-}NO_2C_6H_4CH_3 \rightarrow$$



(a)

$$\textbf{(a)} + 2\,p\text{-}NO_2C_6H_4CH_3 \rightarrow (p\text{-}NO_2C_6H_4CH_2)_2{-} + 2[p\text{-}NO_2C_6H_4CH_3]\cdot^-$$

Simple observation of an ESR signal does not necessarily identify the paramagnetic species. Thus, the photolysis of alkyl hydroperoxides yields a detectable radical species without hyperfine structure, which decays in a second-order process. This decay was ascribed by Piette and Landgraf to the termination reaction of the tertiary alkoxy radicals resulting from photolysis (*19*). However, a consideration of the chemistry involved suggests that the decay almost certainly involves peroxy radicals (*20*).

$$R_3COOH \xrightarrow{h\nu} R_3CO\cdot + HO\cdot$$
$$R_3CO\cdot + R_3COOH \xrightarrow{\text{fast}} R_3COH + R_3COO\cdot$$
$$HO\cdot + R_3COOH \xrightarrow{\text{fast}} H_2O + R_3COO\cdot$$
$$2\,R_3COO\cdot \xrightarrow{\text{slow}} \text{nonradical products}$$

Even the presence of a rich hyperfine structure does not ensure the proper identification of a paramagnetic intermediate. For example, the reactions of

N-nitrosoacetanilide as a phenylating agent have been conceived to involve the diazoanhydride ($C_6H_5N{=}N{-}O{-}N{=}NC_6H_5$) as an intermediate (*21, 22*).

$$C_6H_5N{=}NON{=}NC_6H_5 \rightarrow C_6H_5\cdot + N_2 + C_6H_5N{=}N{-}O\cdot$$

$$C_6H_5\cdot + ArH \rightarrow [C_6H_5ArH]\cdot$$

$$[C_6H_5ArH]\cdot + C_6H_5N{=}NO\cdot \rightarrow C_6H_5Ar + C_6H_5N{=}NOH$$

$$2\,C_6H_5N{=}NOH \rightleftarrows H_2O + C_6H_5N{=}NON{=}NC_6H_5$$

When examined by ESR spectroscopy, the decomposition of *N*-nitrosoacetanilide gave ESR spectra with hyperfine splitting by two nitrogens (a^N = 11.6, 1.7 gauss) and one aromatic ring (a^H = 2.73, 2.60, 2.60, 0.9, 0.9 gauss), consistent with the proposed structure $C_6H_5{-}N{=}N{-}O\cdot$ (*22*). However, it now appears that the observed radical, which has the largest value of a^N associated with the original nitroso group (*23*), actually has the nitroxide structure **5** and can be readily formulated as arising from the attack of a phenyl radical upon the *N*-nitrosoacetanilide (*24*).

$$C_6H_5\cdot + C_6H_5N(NO)COCH_3 \rightarrow C_6H_5N{-}\overset{+}{\underset{\bullet}{N}}(O^-)(C_6H_5)COCH_3$$

5

Other nitroxides are readily found by the addition of radicals to nitroso compounds, including nitrosobenzene (*24*). The ESR observations made in connection with *N*-nitrosoacetanilide decomposition are thus not connected with intermediates in the phenylation reaction, but may instead represent an interesting side reaction (*25*).

When a paramagnetic material is detected in high yield during a reaction, considerably more faith can be placed upon its being a reaction intermediate rather than as an isolated side reaction. The condensation reaction in basic solutions of nitrosobenzene and phenylhydroxylamine to yield azoxybenzene illustrates this type of behavior (*26*). In a very basic medium, such as a solution of potassium *t*-butoxide in dimethylsulfoxide (DMSO), equal molar quantities of nitrosobenzene and phenylhydroxylamine react and give the nitrosobenzene radical anion in a stoichiometric yield.

$$C_6H_5NO + C_6H_5NHOH \xrightarrow[DMSO]{B^-} 2\,C_6H_5NO\cdot^-$$

The nitrosobenzene radical anion can be formed in pure dimethylsulfoxide by the action of hydroxide ion with azoxybenzene, possibly by the reaction sequence

$$C_6H_5N(O){=}NC_6H_5 + OH^- \rightarrow C_6H_5N(O^-)N(OH)C_6H_5 \rightleftarrows C_6H_5N(O^-)N(O^-)C_6H_5 \rightleftarrows 2\,C_6H_5NO\cdot^-$$

In a highly basic solvent, there is no evidence of the conversion of nitrosobenzene radical anions to azoxybenzene. However, in a less basic solvent system, such as hydroxide ion in ethanol, a mixture of nitrosobenzene and phenylhydroxylamine readily condenses to yield azoxybenzene. Under the reaction conditions, nitrosobenzene radical anion can be detected as an intermediate in yields of over 50 percent—based on starting reagents (Fig. 2). Under these conditions, apparently protonation of the dimer derived from nitrosobenzene radical anion can occur. The conversion to azoxybenzene can be readily formulated.

$$2\,C_6H_5NO\cdot^- \rightleftarrows C_6H_5N(O^-)N(O^-)C_6H_5 \rightleftarrows C_6H_5N(OH)N(O^-)C_6H_5 \rightarrow C_6H_5N(O){=}NC_6H_5 + OH^-$$

The ^{15}N and ^{18}O scramblings previously observed (*27*) are now explicable, as well as the formations of four azoxybenzenes from unequally substituted nitrosobenzene and phenylhydroxylamine (*28*).

$$XC_6H_4NO + YC_6H_4NHOH \xrightarrow{B^-} \left\{\begin{matrix} XC_6H_4N(O){=}NC_6H_4X \\ XC_6H_4N(O){=}NC_6H_4Y \\ YC_6H_4N(O){=}NC_6H_4X \\ YC_6H_4N(O){=}NC_6H_4Y \end{matrix}\right\}$$

Since ESR spectroscopy is a sensitive technique capable of detecting radicals at concentrations of 10^{-7} molar, it is

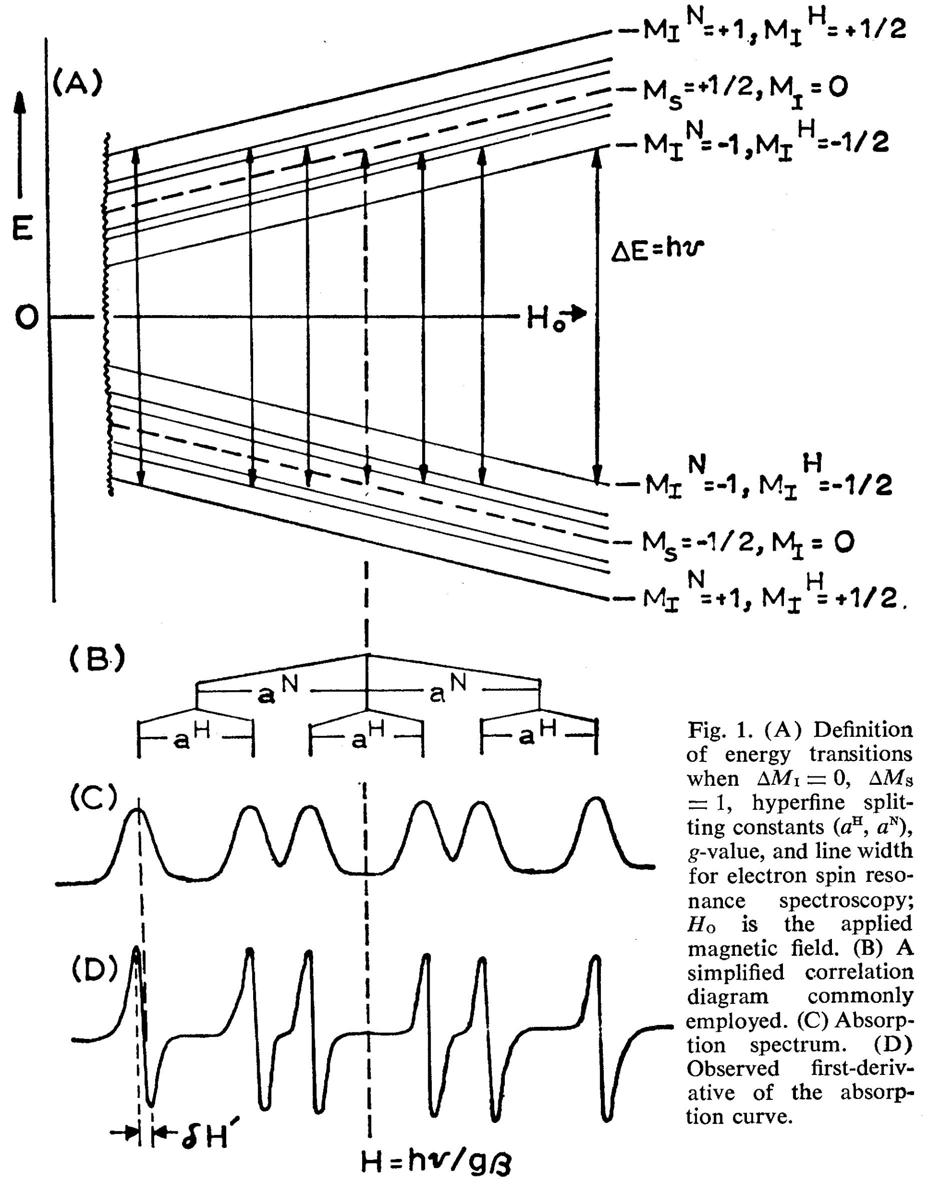


Fig. 1. (A) Definition of energy transitions when $\Delta M_I = 0$, $\Delta M_S = 1$, hyperfine splitting constants (a^H, a^N), *g*-value, and line width for electron spin resonance spectroscopy; H_0 is the applied magnetic field. (B) A simplified correlation diagram commonly employed. (C) Absorption spectrum. (D) Observed first-derivative of the absorption curve.

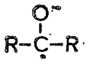
Table 1. Hyperfine splitting in alkyl, aralkyl, and allyl radicals.

Radical	a_α^H (gauss)	$\rho_{C\text{-}\alpha}$
$CH_3\cdot$	23	1.0
$C_6H_5CH_2\cdot$	16.4	0.71
$C_6H_5CH(OH)\cdot$	15.2	0.66
$(C_6H_5)_2CH\cdot$*	8.4	0.36
$CH_2{=}CHCH_2\cdot$	14.4 (avg.)	0.63

* Reference (*82*).

not surprising that numerous errors have arisen in the assignment of structure to paramagnetic substances. Thus, the electrolytic reduction of $\Delta^{2,2'}$-biisobenzimidazolylidene containing 5,6,11, 12-tetraazanaphthacene as an impurity yields the radical anions of the naphthacene and not, as reported, of the imidazolylidene (*29*). Radical anions derived from solvent impurities in alkali metal reductions are often observed. Thus, benzene radical anion has been assigned the adamantane radical anion structure (*30*), and biphenyl and naphthalene radical anions have been often incorrectly identified (*31*).

Electron spin resonance techniques are especially difficult when a decision is to be made between paramagnetic species that might have similar hyperfine splitting patterns. Similar patterns would be expected for the ketyl (**6**), semidione (**7**), and semitrione (**8**) radical anions. In fact, reductions of triketones generally yields the decarbonylated product, the semidione (*32*).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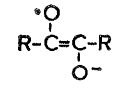
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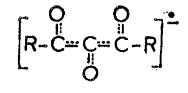
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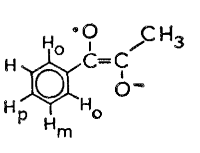
Lown attempted to study a series of ketyls by the addition of alkali metals to cycloalkanones (*33*). The radicals that he actually observed were not the ketyls but oxidation products of the starting ketones, namely the cyclic semidiones (*15*). Electrolytic reduction of ketones in dimethylformamide solution has also been recognized to yield not the expected ketyl but the carbonylation product, the semidione (*34*, *35*).

$$C_6H_5COCH_3 \xrightarrow[\text{potential}]{\text{high}} [C_6H_5COCH_3]^{-2}$$

$$\xrightarrow{(CH_3)_2NCHO} (CH_3)_2NH +$$

$$[C_6H_5COCOCH_3]^{-2} \xrightarrow{-e} C_6H_5C(O\cdot){=}C(O^-)CH_3$$

The semidione and ketyl would have the same hyperfine splitting patterns although the absolute values of the hyperfine splitting constants might be quite different. Indeed, the correctly assigned splitting constants are distinctly different (see **9** and **10**) (*35*, *36*). The assignments of structures are easier if other hyperfine splitting constants (in the present case a^O and $a_{CO}{}^C$) are known (*37*).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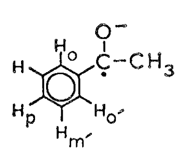
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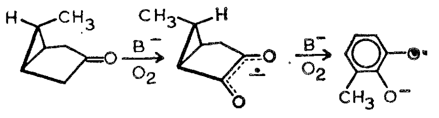
3.43 gauss	$a_{CH3}{}^H$	6.74 gauss
1.59	$a_o{}^H$	3.71, 4.24
0.53	$a_m{}^H$	0.88, 1.07
1.84	$a_p{}^H$	6.60

Even more subtle molecular transformations may be detected during ESR investigations. Thus, we have recently shown that *syn*-6-methylbicyclo[3.1.0] hexane-3-one (**11**) is oxidized in basic solution consecutively to a semidione (**12**) and a semiquinone (**13**), but with molecular rearrangement in each transformation (*38*).



11 **12** **13**

Delocalization of an Unpaired Electron

Hyperfine splitting by hydrogen atoms in an organic radical is a measure of spin density in the 1*s* orbital. Hyperfine splitting by any nucleus is given by

$$a = -\frac{8}{3}\pi g_I u_I g_e u_e \,|\, \psi\,(O)|^2$$

where g_I and g_e are g-factors for the nucleus and electron. For organic radicals these factors do not vary significantly and variations in hyperfine splitting constants can be related to $|\psi(O)|^2$. Radicals with the unpaired spin in a p or π orbital, such as methyl radical or benzene radical anion, show hyperfine splitting by the hydrogen atoms in the nodal planes. This is a result of spin polarization which places a negative spin density on the hydrogen atom (that is, a spin density opposite in sign to that seen by the molecule as a whole). This

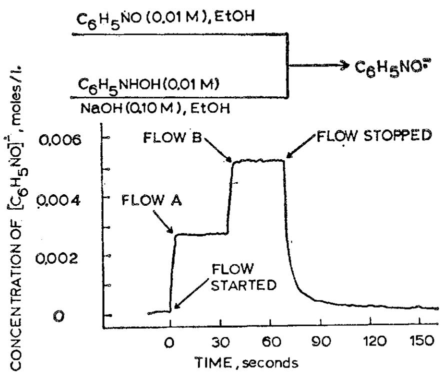
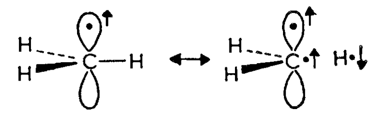


Fig. 2. Radical concentration as measured by electron spin resonance absorption at constant field for reaction products of nitrosobenzene and phenylhydroxylamine in a stopped flow apparatus at 23° ± 1°C. After mixing, the solutions were 0.005*M* in each reagent and 0.05*M* in hydroxide ion. *Flow A*, radical detected 3 seconds after mixing; *flow B*, 0.5 second after mixing.

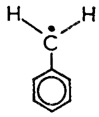
interaction does not affect the p or π electron density of the unpaired spin and provides a partial mechanism for

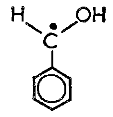


hyperfine splitting by the ^{13}C nuclei as well as by hydrogen atoms in the nodal plane. The magnitude of this interaction is given by the expression (*39*) where

$$a^H = Q_{CH}{}^H \rho_C$$

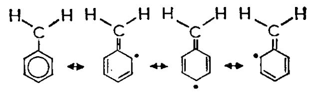
ρ_C is the spin density in the p_z orbital and $Q_{CH}{}^H$ is a number between −22 and −28. This number depends on charge and upon bond angles of the planar carbon atom (*40*). By use of this relation, an experimental spin density can be deduced for a planar π radical or radical ion. The delocalization of the odd electron in the benzyl radicals exemplifies this approach (structures **14** and **15**) (*41*).


Formula **14**

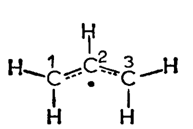

Formula **15**

16.4 gauss	$a_\alpha{}^H$	15.2 gauss
5.17, 5.17	$a_o{}^H$	4.62, 5.17
1.77, 1.77	$a_m{}^H$	1.63, 1.63
6.19	$a_p{}^H$	5.88
	$a_{OH}{}^H$	0.47

The nonequivalence of the *ortho* and *meta* hydrogen atoms of the α-hydroxybenzyl radical demonstrates the planarity and restricted rotation of the benzylic radical. Positive spin density at the *ortho* and *para* positions is expected because of conjugation.



However, the hyperfine splitting by the hydrogen atoms in the *meta* position is surprising and unexpected from the basic Hückel molecular orbital approach. Again, spin polarization has been invoked to create a negative spin density at the *meta* positions (*42*). Since the total spin density must be 1.00, the positive spin density will be greater than 1.0. In a similar fashion appreciable negative spin density is observed at the central carbon atom of the allyl radical (structure **16**, $Q_{CH}{}^{H} = -24.7$ gauss) (*8, 43*).



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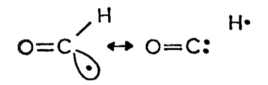
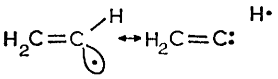
a^H = 13.93 (2), 14.83 (2), 4.06 gauss
$\rho_{C\text{-}1} = \rho_{C\text{-}3} = +0.58$, $\rho_{C\text{-}2} = -0.16$

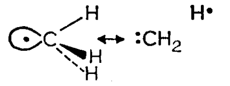
Hydrogen atoms attached to a carbon atom with an unpaired electron in a hybrid orbital also undergo interaction owing to overlap between the orbitals containing the unpaired electron and the carbon-hydrogen bond.



$a^H = 137$ gauss (*44*)



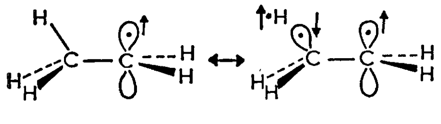
$a^H = 13.4$ gauss (*9*)



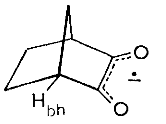
$a^H \approx +15$ gauss (*45*)

It is predicted (*45*) that, for a tetrahedral methyl radical, the value of a^H will be approximately +15 gauss (experimentally a^H is −23 for the planar methyl radical) (*46*).

Hydrogen atoms attached to carbon atoms adjacent to the unpaired spin undergo interaction with the unpaired spin. This interaction is usually described as hyperconjugation and is a maximum when the carbon-hydrogen bond and orbital are coplanar (*47*).

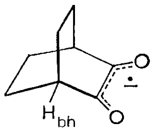


The interaction follows a $\cos^2\theta$ relation, $a^H = \beta\rho_C\cos^2\theta$ where θ is the dihedral angle between the C-H bond and the *p* orbital and β is a constant between 20 and 60 gauss (*48*). Thus, interaction with the bridgehead hydrogen (H_{bh}) of **17** but not **17** ($\theta = 90°$) is seen (*49*).



17

$a_{bh}{}^H = 2.5$ gauss



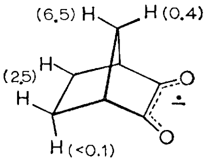
18

$a_{bh}{}^H < 0.1$ gauss

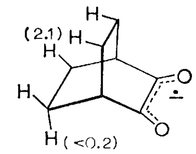
In general, hyperfine splitting by hydrogen atoms is important only at the 1- or 2-position (*alpha*) in a radical.

$CH_3CH_2CH_2CHR$
4 3 2 1
γ β α

Hyperfine splitting by β-hydrogens in acyclic radicals can be barely detected in most cases. However, in rigid molecules possessing a highly bridged structure, such as **17a** or **18a** hydrogen atoms β to the radical site undergo a strong interaction (*49*).

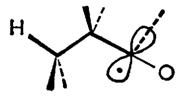


17a



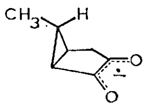
18a

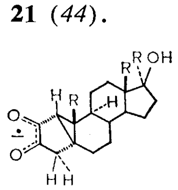
The interaction in **17a** or **18a** fits a double V arrangement (**19**) (*50*). In **19** the coplanar arrangement of the three bonds (H–C–C–C) and one-half of the *p* orbital containing the unpaired electron define the double V.



19

Longer range interactions can be seen. In particular, 2½ V interactions are seen in **20** and **21** (*44*).



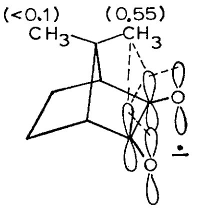


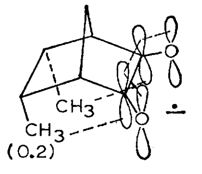
20 **21**

$a_{CH_3}{}^H = 0.4$ gauss R = CH_3,
a^H = 13.9, 7.6, 4.8, 1.5 gauss

In rigid systems with the appropriate geometry, one can expect to see these delocalizations when the carbon-hydrogen bond and the carbon p_z orbital are in a V, 1½ V, 2 V, 2½ V arrangement.

Other geometries can give rise to a long-range hyperfine splitting by hydrogen atoms. In particular, any arrangement that places the back side of a carbon atom in close proximity to an orbital containing unpaired spin density will be expected to lead to interaction. The *syn*-7-methyl group of 7,7-dimethylbicyclo[2.2.1]heptane-2,3-semidione or the *endo*-methyl groups of *endo, endo*-5,6-dimethylbicyclo[2.2.1]heptane-2,3-semidione illustrates this phenomenon (**22** and **23**).



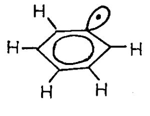


22 **23**

The long-range interaction exemplified by the 2 V or 2½ V arrangement as well as by **22** and **23** can be considered examples of homohyperconjugation (*51*).

It is apparent that ESR spectroscopy provides direct experimental proof for bonding interactions of extraordinary nature—interactions of a type that are not predicted in any way by the concepts of the electron-pair bond (Lewis bond) or Hückel molecular orbitals. It is of interest that many of these interactions are predicted by the Hückel molecular theory as extended by Hoffmann (*52*).

Electron spin resonance can readily distinguish between a σ and a π structure for a radical. The phenyl radical could conceivably have the electronic structure **24** or **25**.



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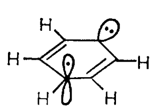
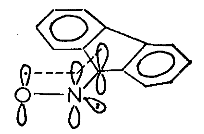


25

Structure **25** would predict interaction with all aromatic hydrogen atoms. Since it is reported that in the phenyl radical only the *ortho* (18.1 gauss) and *meta* (6.4 gauss) hydrogen atoms are seen (*53*), structure **25** can be discarded. Similarly, for the iminoxy radical derived from fluorene structures **26** and **27** can be differentiated.



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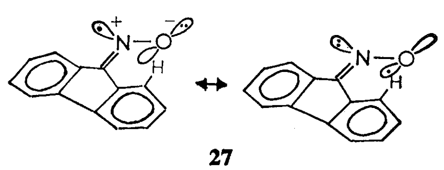

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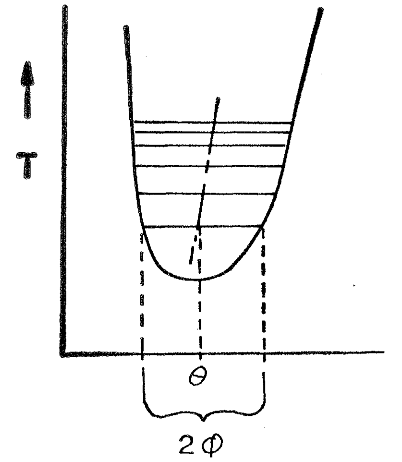


Fig. 3. Potential energy well describing equilibrium dihedral angle (θ) and vibrational motion ($\pm \phi$) in the lowest energy level.

Structure **26** (a π radical) would predict delocalization of the unpaired spin over all the aromatic carbon atoms. Structure **27** predicts that the unpaired spin would be fixed on the oxygen and nitrogen atoms. This structure (a σ radical) is preferred because the experimental spectrum shows that a^N is equal to 31 gauss and a^H, 2.7 gauss (*54*). The hyperfine splitting by the single hydrogen atom indicates another type of through-space interaction between the electron spin and the proton nuclear spin. The term *through space* is used to indicate an interaction that cannot be explained by a polarization of the electrons in the bonds separating the nuclear and electron spin.

Hyperfine splittting by hydrogen atoms attached to or *alpha* to a paramagnetic center will reflect delocalization of the unpaired spin. Accurate estimates of this delocalization can be made provided the values of $Q_{CH}{}^H$ or $Q_{CCH_3}{}^H$ are unaffected by substitution. When the methyl radical ($CH_3\cdot$), benzyl radical ($C_6H_5CH_2\cdot$), 1-hydroxybenzyl radical ($C_6H_5CH(OH)\cdot$), and allyl radical ($CH_2{=}CHCH_2\cdot$) are compared, considerable spin delocalization is indicated ($Q_{CH}{}^H = -23$ gauss) (Table 1). Note that delocalization can be partially compensated by spin polarization; for example, for allyl radical, delocalization alone predicts $\rho_{C\text{-}1} = \rho_{C\text{-}3} = 0.500$.

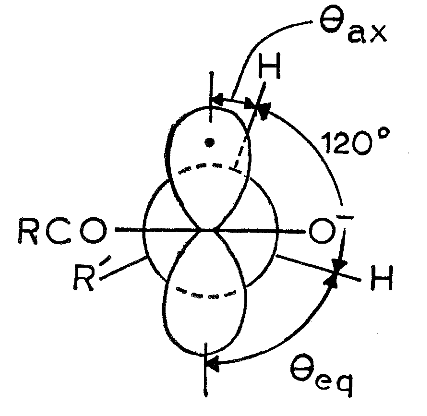


Fig. 4. Definition of equilibrium dihedral angles for cyclic semidiones.

The Geometry of Free Radicals

Electron spin resonance spectroscopy presents a time-averaged view of the geometry of a paramagnetic species. Because of the velocity of precession of the magnetic moment connected with the unpaired electron spin around the applied magnetic field, ESR spectra reflect a time-averaged period about 1000 times shorter than proton magnetic resonance. Thus, in proton magnetic resonance at 60 megahertz *cis*-decalin is rapidly time-averaged between the two chair conformations. On the other hand, the conformationally less stable *cis*-decalin-2,3-semidione appears to be conformationally frozen at 25°C by ESR spectroscopy (see Chart 2) (*17*).

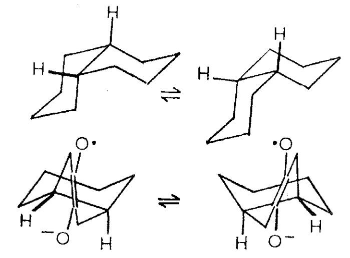
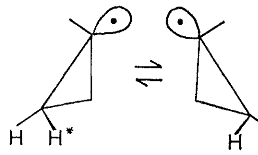


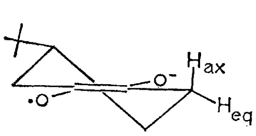
Chart 2

Of course, even at absolute zero not all vibrational motion is necessarily frozen in a molecule, and time-averaging of a nucleus about some equilibrium position may still be occurring (Fig. 3). However, at the lowest possible temperature, conformational interconversion will no longer be occurring since this requires an energy of activation. It should also be noted that for a symmetrical system an equilibrium dihedral angle (θ) of 0 or 90 degrees (relative to the plane of a p orbital) will never be observed if vibrational motion still occurs in the zero vibrational level. Instead a time-averaged dihedral angle between the limits $\theta \pm \phi$ will be observed (*55*).

The similarity in values of $Q_{CH}{}^H$ for methyl radicals (-23.0 gauss) and the benzene radical anion (-22.5 gauss) suggests similar geometries, that is, $\theta = 90°$, ϕ is small. Estimates of ϕ may be obtained by a careful measurement of values of a^H/a^D since the value of ϕ should change with isotopic substitution (the magnetic moments of hydrogen and deuterium nuclei are in the ratio of 6.514 to 1.000) (*45*, *56*, *57*). The value of $a_{CH_3}{}^C$ equal to 38 gauss for methyl radical is also characteristic of the planar radical (*45*, *58*). An electron in a 2*s* orbital of carbon would have a value of a^C equal to 1200 gauss, and in an sp^3 orbital, a value of a^C equal to $1200/4 \cong 300$ gauss (*57*). Experimentally the trifluoromethyl radical ($CF_3\cdot$) and the difluoromethyl radical ($CF_2H\cdot$) give values of a^C equal to 271 and 149 gauss, respectively. These radicals are apparently not planar. The cyclopropyl radical with $a_{CH}{}^H$ equal to $|6.5|$ gauss is apparently a tetrahedral radical with the free electron in an orbital with a large amount of *s*-character. Since the methylene atoms appears to be equivalent, the two conformations must be equally populated at -120°C (*9*, *45*).



The ESR spectra of cyclohexane semidiones have been carefully examined in regard to equilibrium and dynamic geometries. The spectra of 4-*t*-butylcyclohexane semidione or *trans*-decalin-2,3-semidione do not undergo any significant change with temperature between $-100°$ and $+80°$C. The α-hydrogen atoms exist as two pairs ascribed to equatorial and axial hydrogen atoms (**28**) (*60*). The 4-*t*-butyl group or the *trans* (diequatorial) fused tetramethylene ring impart conformational stability. In both systems $a_{ax}{}^H/a_{eq}{}^H \approx 2$. There is a small increase in the absolute values of $a_{ax}{}^H$ or $a_{eq}{}^H$ with temperature, which may be connected with spin density variations; but the ratio of $a_{ax}{}^H/a_{eq}{}^H$ remains constant. One can solve for the equilibrium dihedral angle θ if it is as-



28

sumed that φ can be neglected by simultaneous solution of the equations (*16*)

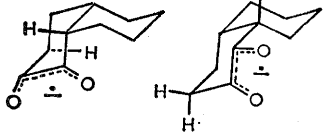
$$a_{ax}^{H} = \rho_{C}B\cos^{2}\theta_{ax}$$
$$a_{eq}^{H} = \rho_{C}B\cos^{2}\theta_{eq}$$

If θ_{ax} is assumed to be equal to $\theta_{eq} - 60$ degrees (Fig. 4), it can be calculated that θ_{ax} is + 13 degrees and $\rho_C B$ is 13.8 gauss ($a_{ax}^{H} = 13$; $a_{eq}^{H} = 6.5$ gauss). The simultaneous estimation of θ and φ from experimental evidence is a challenging problem. Using the ethyl radical or *m*-xylene radical anion as models to estimate B, we obtain ρ_C equal to 0.24 to 0.35. By difference, ρ_O is 0.15 to 0.26. About 8 percent of the unpaired spin

$$([2(13) + 2(6.5)]/508 \cong 8 \text{ percent})$$

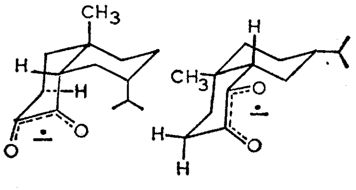
is delocalized onto the α-methylene hydrogen atoms by hyperconjugation (*61*).

In the *cis*-decalin-3,4-semidione we have the possibility of population of two conformations, the steroidal conformation (S) and the nonsteroidal conformation (NS).



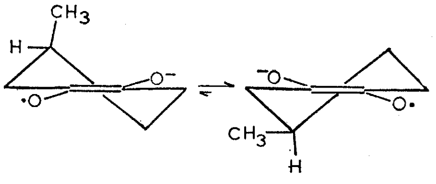
S NS

The observation of a spectrum with hyperfine splitting by two hydrogen atoms (axial) and by one smaller one (equatorial) defines the preferred conformation as steroidal (S) (*62*). On the other hand, the corresponding semidione, derived by oxidation of the 1-position of valeranone, displays hyperfine splitting by one axial hydrogen and two equatorial hydrogen atoms. Again, the conformation of the semidione is defined; but now the nonsteroidal conformation is preferred because the isopropyl group demands the equatorial position.



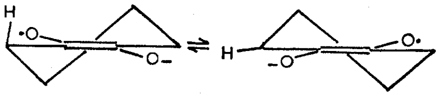
S NS

When 3- or 4-methylcyclohexanesemidiones are cooled below 25°C a considerable change in the hyperfine splitting constants is observed. In the range of −100°C the spectrum for 4-methylcyclohexanesemidione becomes similar to that observed for 4-*t*-butylcyclohexanesemidione at 25°C. 3-Methylcyclohexane semidione behaves similarly except that at −100°C only one *alpha* equatorial hydrogen atom is seen. These results are consistent with the presence of unequally populated conformations at the high temperatures but only a single (blocked) conformation at −100°C.



Axial-methyl Equatorial-methyl

The enthalpy difference between the axial and equatorial methyl group is 1.2 for the 4-methyl and 0.7 kilocalories per mole for the 3-methyl group. Cycloanesemidione, and symmetrically substituted cyclohexane semidiones such as the 3,3-dimethyl, 4,4-dimethyl, or 3,3,5,5-tetramethyl derivatives, show a different effect of temperature. At +80°C time-averaging of the two conformations occurs, and either four or two *alpha* hydrogen atoms with a^{H} equal to $(a_{ax}^{H} + a_{eq}^{H})/2$ are seen. Figure 5a illustrates this for 3,3-dimethylcyclohexane semidione. As the temperature is lowered the rate of conformational interconversion decreases and certain lines in the spectrum, in the case of Fig. 5 the central line, become broader. This broadening occurs because of statistical considerations. Conformational interconversion, A ⇄ E, causes equatorial and axial hydrogens to exchange position. Certain combinations of the sign of the nuclear spin of these *alpha* hydrogen atoms will result in a change in spin states (that is, energy levels) upon ring flip. At high temperatures, the ring flip will be sufficiently fast that a given molecule will spend exactly 50 percent equal time in each $\Sigma M_I = 0$ spin state of the time in each conformation.



A E

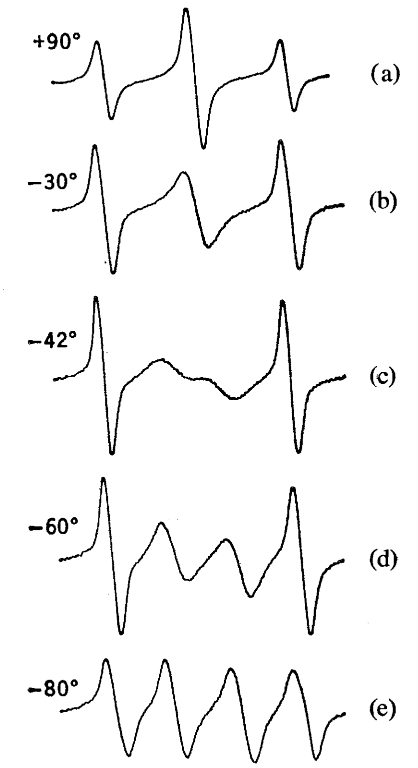
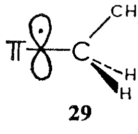


Fig. 5. First-derivative electron spin resonance spectra of 3,3-dimethylcyclohexane semidione (cesium salt) in dimethylformamide solution. The triplet-splitting at +90°C represents $a^{H} = 9.3$ gauss; at −80°C the 1 : 1 : 1 : 1 quartet requires $a^{H} = 13.00$ and 6.50 gauss.

At lower temperatures during the period of precession of the magnetic moment of the nuclear spin about the magnetic moment associated with the unpaired electron, not all molecules will spend exactly 50 percent of the time in each of the two equally populated conformations. This results in a broadening of those lines which correspond to transitions for which conformational interconversion results in a change in spin state. Further lowering of the temperature (Fig. 5c) causes a further decrease in the ring inversion rate, and eventually a temperature is reached at which the originally double degenerate central line for 3,3,5,5-tetramethylcyclohexanesemidione splits into two separate lines. This is the coalescence temperature and corresponds to conformational lifetimes of about 10^{-6} second. For still lower temperatures slower rates of ring inversion are observed, and two kinds of *alpha* hydrogen atoms are seen: those that spend most of their time in the axial position and those that spend most of their time in an equatorial position. Further cooling causes an increase in the percentage of time during which every molecule occupies a specific conformation, and the spectrum approaches that of a frozen or blocked conformation when the conformational lifetime is more than 10^{-6} second.

Another commonly encountered example of conformation preference occurs when methyl, ethyl, and isopropyl groups are attached to an unsaturated paramagnetic center (π) (*55*, *63*). For the methyl group, free rotation nearly always occurs, and the time-average value of θ is 45 degrees. For ethyl, and to a greater extent for isopropyl, conformations are populated so that the *alpha* hydrogen atom is close to the nodal plane, for example **29** to **31**.



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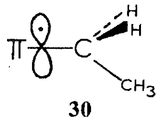

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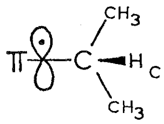

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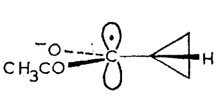

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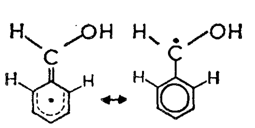
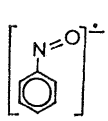
The net result is that a^{H} decreases from $-\mathrm{CH}_3$ to $-\mathrm{CH}_2\mathrm{R}$, and sharply decreases in $-\mathrm{CHR}_2$ in these systems. An extreme case of conformation preference occurs when a cyclopropyl group is attached to a paramagnetic center having a positive charge density on the carbon atom attached to the cyclopropane ring, such as **32** (*64*, *65*). Here the methine hydrogen atom is very nearly in the nodal plane. Restricted rotation is observed in many phenyl-submitted radicals in which a partial double bond is created by delocalization. Restricted rotation can be expected to result in magnetically nonequivalent *ortho* hydrogen atoms. The acetophenone ketyl (**9**) and α-hydroxybenzyl radical (**15**) illustrate this effect.



Numerous *N*-phenyl radicals show this effect including structures **33** to **35** (*66*). In these latter one *ortho* hydrogen atom is magnetically equivalent to the *para* hydrogen atom (*66*). The unique aromatic hydrogen atom is the second *ortho* hydrogen atom. Of course, the hyperfine splitting patterns of structures **33** to **35** does not suggest restricted rotation upon cursory inspection, because the equivalent hydrogen atoms could be assigned to the *ortho* positions (*67*). However, *para* substitution reveals the fortuitous magnetic equivalence and restricted rotation.



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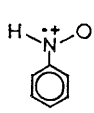

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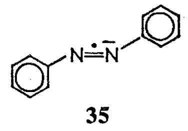

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Lifetimes of Paramagnetic Species

Electron spin resonance spectroscopy can be used to measure the rate of decay of a paramagnetic substance. Thus, the decay curve of Fig. 2 yields a second-order rate constant of 1.4×10^2 liter mole^{-1} sec^{-1} for the disappearance of nitrosobenzene radical anions. Much faster processes can be measured by ESR spectroscopy and, in particular, processes involving conformational interconversions. At the standard ESR magnetic field, the magnetic moment of the unpaired electron precesses about the applied magnetic field in 10^{-10} second. However, sharp ESR lines cannot be obtained if the individual spin states have a lifetime of this order of magnitude. For sharp ESR lines the lifetimes of spin states involved in an energy transition must be in the range of 10^{-6} second. This can be deduced from the Heisenberg uncertainty principle, $\Delta E \Delta t \geq h/2$, where ΔE is the energy of the transition and Δt the time available for the measurement. For a radical with $g = 2$ this expression reduces to $\Delta H \Delta t \geq 6 \times 10^{-8}$, where ΔH is the line width of an individual ESR peak. To achieve reasonably sharp lines ($\Delta H \sim 0.1$ gauss), Δt must be in the range of 10^{-6} second. If, within this time period, one spin state is converted into another, then line broadening will occur. A variety of electron-transfer identity reactions have been investigated by this technique, including reactions 1 and 3 (*68*).

$$(p\text{-NO}_2\text{C}_6\text{H}_4)_3\text{C}\cdot + (p\text{-NO}_2\text{C}_6\text{H}_4)_3\text{C}:^- \rightleftarrows (p\text{-NO}_2\text{C}_6\text{H}_4)_3\text{C}:^- + (p\text{-NO}_2\text{C}_6\text{H}_4)_3\text{C}\cdot \quad (3)$$

The second-order rate constant for these processes is given by,

$$k = (\sqrt{3}\pi)(2.83 \times 10^6)\Delta\Delta H/N$$

where $\Delta\Delta H$ is the increase in line width (peak to peak separation of first derivative spectrum) introduced by the exchange, and N is the concentration of the diamagnetic species involved in the reaction. In these identity reactions, line broadening occurs because the transfer of the electron from some specific orientation involving the eight-proton nuclear spins for naphthalene radical anion (or 12 proton nuclear spins and three nitrogen nuclear spins for the tris-*p*-nitrophenylmethyl radical) will occur statistically to all possible other orientation of the eight-proton spins in naphthalene. In most electron transfers, one spin state will be destroyed and another created. Of course, when electron transfer becomes very fast, the spin states will lose identity, the hyperfine splitting will disappear, and the ESR spectrum will be a single sharp line, as would be seen for a free electron.

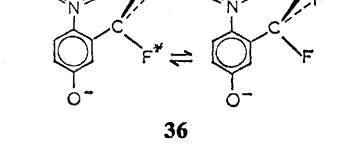
In ESR spectroscopy, the electron magnetic moment can be imagined to precess around the axes of the nuclear magnetic moments as well as the direction of the applied magnetic field. A splitting constant (a) of 1 gauss corresponds to a frequency of 2.83×10^6 hertz or $3.6 \times 10^{-7}/a$ seconds per cycle. If, in a significantly shorter time, the magnetic field of the nucleus at the electron is averaged, then a line-broadened or time-averaged spectrum will result.

When this time averaging involves a nucleus in two magnetic environments, such as axial and equatorial hydrogen atoms in cyclohexane semidione, a unique exchange rate exists below which the two different magnetic environments can be distinguished. This coalescence rate is given by the expression

$$k = 6.22 \times 10^6 \, (a_{\mathrm{A}}{}^{\mathrm{H}} - a_{\mathrm{B}}{}^{\mathrm{H}})$$

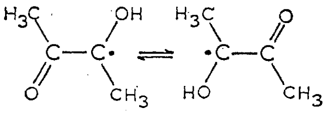
where $a_{\mathrm{A}}{}^{\mathrm{H}}$ and $a_{\mathrm{B}}{}^{\mathrm{H}}$ are the hyperfine splitting constants in gauss for magnetic environments A and B (*69*). For 3,3-dimethylcyclohexanesemidione this rate occurs at $-42°$C (Fig. 5). The conformational lifetime ($1/k$) or half-life [$(\ln 2)/k$] can be readily obtained. Rate constants can also be deduced from line broadening above the coalescence temperature, and the peak separation below this temperature.

Lifetimes of spin states destroyed by hindered rotation, can be measured in certain cases such as **36** (*70*). In addi-



36

tion, some fast chemical reactions are amenable to study. One example is the rate of proton exchange in protonated biacetyl semidione (**37** ⇄ **38**) wherein the magnetic environment of the six hydrogen atoms changes (*71*). A similar effect has been noted for protonated semiquinones (*72*).



37 **38**

Electron spin resonance spectroscopy can measure rather short lifetimes and rapid rates for spin state interconversions. However, there are some limitations in the actual measurement of chemical lifetimes, say by a rapid flow technique. If the chemical lifetime is short, the steady-state concentration of radicals will be small and detection becomes a problem. Another serious problem is that techniques for the generation of radicals cause them to be formed in a saturated condition, that is, both electron spin states equally populated. Before the energy transitions of Fig. 1 can be observed a Boltzmann population of energy levels must be approached. This requires considerable time by thermal relaxation; often as long as 10^{-4} second. The fact that this relaxation process is relatively slow not only limits chemical lifetime measurements by ESR but also makes concentration measurements of short-lived species a qualitative measurement.

Assignment of Structure by Electron Spin Resonance Spectroscopy

Electron spin resonance spectroscopy can be used as a tool for structural assignment. We are, in general, faced with the problem of converting a diamagnetic substance into a specific type of paramagnetic material whose *g*-value and hyperfine splitting constants will provide valuable information concerning the structure close to the position of the unpaid spin. Potentially, any unsaturated system can be oxidized or reduced to the radical cation or anion. Specifically, the oxidation of polynuclear hydrocarbons to radical cations by sulfuric acid (*73*) and their reduction to radical anions by alkali metals in dimethoxyethane or tetrahydrofuran deserves mention (*74*). Aromatic nitrocompounds (*75*), nitriles (*76*), and ketones are readily reduced to the radical anions while alkoxybenzenes are readily oxidized to radical cations (*77*). Amines and hydroxylamines can be oxidized to nitroxides and oximes to ketoximes. Quinones can be reduced and hydroquinones oxidized to the semiquinone (*78*).

The most widely investigated group of paramagnetic materials are the semidiones which are readily prepared by the routes shown in Chart 3.

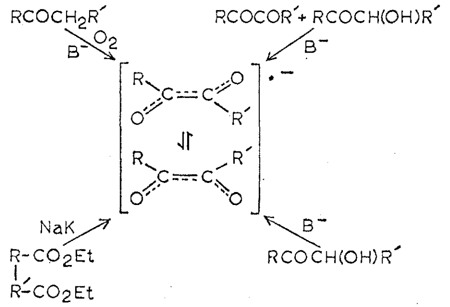


Chart 3

The conversion of the three isomeric methylcyclohexanes to semidiones illustrates one application of the technique (*79*). 2-Methylcyclohexanone yields a single semidione with hyperfine splitting by three magnetically different hydrogen atoms (eight lines of unit intensity). 4-Methylcyclohexanone yields a single semidione that includes hyperfine splitting by two pairs of hydrogen atoms. Finally, 3-methylcyclohexanone yields a mixture of the above semidione in the ratio of 1:3. The only structural assignment consistent with the structure of the starting ketones and observed semidiones is that given in Chart 4. The structure proof is essentially a proof based on first principles, since the mixture of semidiones (from the 3-methyl compound) is uniquely assigned to that ESR spectrum whose peaks decay at different rates (3-methylcyclohexanesemidione is less stable than 4-methylcyclohexanesemidione).

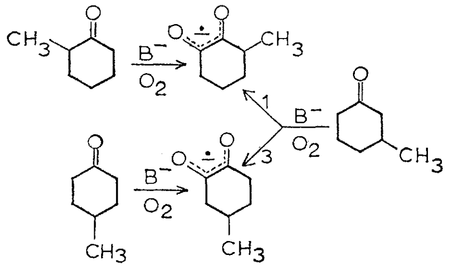
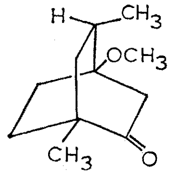


Chart 4

The *cis*- and *trans*-β-decalones can readily be identified by this technique. Figure 6 illustrates the great difference in the mixture of semidiones derived from the oxidation of 5α- and 5β-3-keto-19-nor steroids. Not only are the spectra empirically different but the Δ^2-semidiones (semidione with a partial double bond between carbon atoms number two and three) can actually be differentiated on a first-principle argument, and the configuration at carbon-5 in the starting ketone can be defined. Thus, the 5α-ketone yields a Δ^2-semidione that is a derivative of the rigid *trans*-decalin-2,3-semidione. Hyperfine splitting by two pairs of α-hydrogen atoms are seen. The 5β- compound yields a derivative of *cis*-decalin-2,3-semidione. As in the parent *cis*-decalin, the four alpha hydrogen atoms are magnetically nonequivalent, and a spectrum requiring four doublet hyperfine splitting constants is observed. Both the 5α- and 5β-3-ketone give rise to a second radical identified as the *trans*-Δ^3-5α-semidione (epimerization having occurred for the 5β-3-ketone).

The application of this technique to a substance of unknown structure is illustrated by application to 1,5-dimethyl-4-methoxy-bicyclo[2.2.2]octane-2-one (**39** or **40**) (*49*, *80*).



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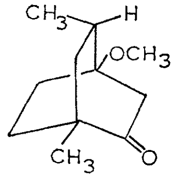
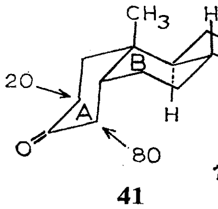


40

Oxidation yielded a semidione with hyperfine splitting by four hydrogen atoms (a^H = 2.1, 2.1, 2.1, 0.9 gauss). Since only **39** would yield a semidione having four hydrogen atoms in a double V arrangement, the structure seems secure.

Inferences can be made about the conformational structure of the starting ketones (*62*). The 5β-3-ketone (**41**) oxidizes to yield a mixture of semidiones resulting from attack at carbon-4 (80 percent) and carbon-2 (20 percent). This rigid steroid structure must have the configuration shown, and the particular arrangement of the A to the B ring is called the steroid configuration. On the other hand, the carbon-8,9 epimer of **41** (that is, **42**) oxidizes only at carbon-2.



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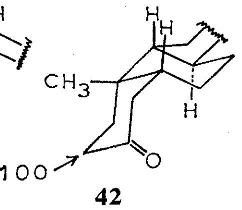
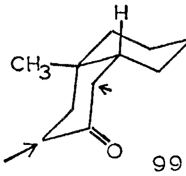


42

This difference in position of attack can be assumed to be definitive of the steroidal (**41**) and nonsteroidal (**42**) configurations. When applied to *cis*-β-decalone, the preferred point of oxidation is at the *alpha* position, and the steroidal conformation (that is, a conformation analogous to the rigid configuration of **41**) is indicated However, when applied to *cis*-2-keto-10-methyldecalin (**43**) the preferred point of oxidation is at carbon-3 (analogous to carbon-2 in **42**). We thus conclude that *cis*-2-keto-10-methyldecalin exists in the nonsteroidal conformation. This view is substantiated by the exclusive oxidation of valeranone at carbon-3 (**44**). A similar approach has shown that 2-keto-9-methyl decalin also reacts preferentially in the nonsteroidal conformation (*62*).



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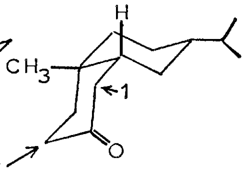
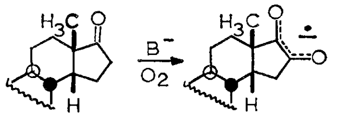


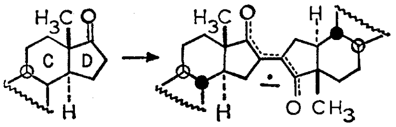
44

Compounds **41** to **44** emphasize that, in certain instances, inferences can be drawn about structure at points far enough removed from the paramagnetic center that hyperfine splitting at the site of structural change is not seen. Analyses based on more complex chemical reasoning can be imagined. I will conclude with an eminently practical example of an analysis for the relation between rings C and D—whether *cis* or *trans*—in 17-keto-derivatives of perhydrophenanthrene (*81*). Empirically we have shown that these fused rings compounds the structure in which C and D are *cis*, react normally to yield the expected semidione, **45** (Fig. 7a).



45

However, of those examined every 17-ketone with C and D rings in *trans* position has yielded a dimeric radical anion (**46**) whose spectrum is readily distinguished from that of **45** (Fig. 7b).



46

Here it can be proved that the initially formed α,β-diketone readily condenses with a molecule of the starting ketone to yield the unsaturated diketone precursor to **46**.

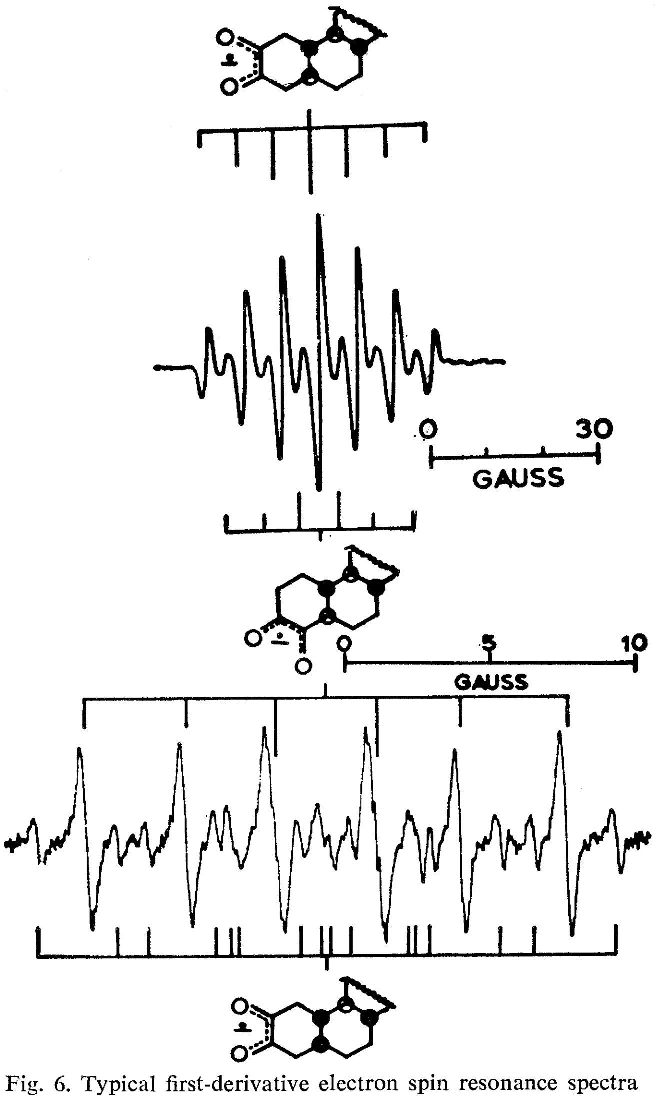


Fig. 6. Typical first-derivative electron spin resonance spectra observed in the base-catalyzed oxidation of 19-nor-3-keto steroids (or the enantiomeric 18-nor-D-homo-17-keto steroids) with A to B (or C to D) ring fusion being *cis* and *trans*. Top spectrum, 3-methoxy-D-homo-18,19-bisnorandrost-1,3,5(10)-triene-17-one (*trans* ring fusion); bottom spectrum, 3-methoxy-D-homo-18,19-bisnor-13α,14α-androsta-1,3,5(10)-trien-17-one (*cis* ring fusion).

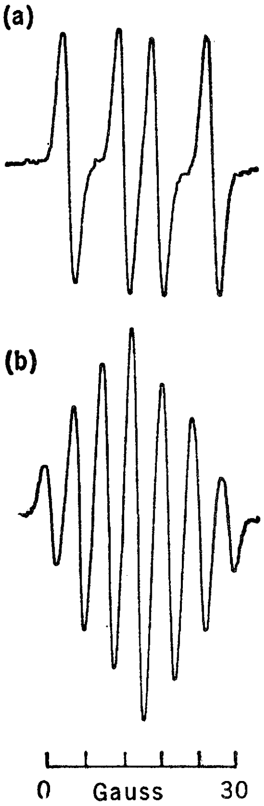


Fig. 7. First-derivative electron spin resonance spectra (25°C) of semidiones derived from oxidation of dimethylsulfoxide solutions of potassium *t*-butoxide and (a) 3β-hydroxy-13α, 13α-androst-5-en-17-one (*cis* C to D ring juncture), (b) 5α-androstan-17-one (*trans* C to D ring juncture). Spectrum (a) requires $a^{\mathrm{H}} = 14.23$ and 8.80 gauss. Spectrum (b) requires $a^{\mathrm{H}} = 9.34$, 9.34, 4.67, 4.67 gauss.

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